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AUTHOR Tsutakawa, Robert K.
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ABSTRACT

This report describes new statistical procedures for item response analysis using estimation of item response curves used in mental testing with ability parameters treated as a random sample. Modern computer technology and the EM algorithm make this solution possible. The research focused on the theoretical formulation and solution of maximum likelihood and Bayesian estimations of item parameters. Algorithms were developed and numerically illustrated for the one and two parameter logistic models. Results are comparable to conventional methods treating ability parameters as fixed. These new methods produce estimates when they do not exist under older methods. The Bayesian approach yields an approximation to the posterior covariance matrix, which can be used to make probabilistic statements about the uncertainty of the estimated parameters. User oriented computer packages need to be prepared before widespread application of these methods can be made. (Author/BS)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the main findings of a research conducted under ONR contract N00014-81-K-0265, NR-150-464, during the period May 16, 1981 - September 30, 1984. The research focused on the estimation of parametric item response curves under the assumption that univariate ability parameters are sampled from some parametric population distribution. Both maximum likelihood and Bayesian approaches have been studied and compared to the more convential approaches where abilities are treated as fixed parameters.

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Improved Estimation Procedures for Item Response Functions

by

Robert K. Tsutakawa

Research Report 84-2

October 1984

Department of Statistics

University of Missouri

Columbia, MO 65211

Introduction

The overall objective of the research is to develop new statistical procedures for estimating item response curves used in mental testing. A typical test, which is studied here, consists of K test items administered to n examinees. The data consists of a matrix of binary scores indicating which items are scored correctly and which incorrectly by each of the examinees.

The analysis of such data is based on an assumed model which specifies the probability of correct response to each item as a function of the ability of the examinee. Such probability models can be indexed by item parameters. The main result of this research is the development of new methods for estimating these item parameters for the purpose of measuring abilities based on such estimates.

When abilities are defined in terms of real variables and treated as fixed effects, both theoretical and practical analysis of item responses are greatly hampered by the large number of parameters, which increases as the number of examinees, n, increases. The standard method for simultaneously estimating item and ability parameters is maximum likelihood, using standard programs such as LOGIST described in Wingersky, Barton, and Lord (1982). Some of the problems encountered by this approach are the occassional non-existence of a true maximum likelihood solution and the lack of a reasonable measure of the reliability of the estimated parameters.

The approach taken by the current research assumes that ability parameters are sampled from some population distribution, which itself may be indexed by parameters. The true likelihood function then becomes the integral of the conventional likelihood function with respect to the ability distribution. The resulting likelihood function is then a function of the item parameters and the "hyperparameters" of the unknown ability distribution. Though the resulting expression for the likelihood function is not simple, it contains substantially fewer parameters then the conventional maximum likelihood equations. A general approach to finding the maximum likelihood estimate using the new likelihood function is the EM algorithm, discussed in its general form by Dempster, Laird, and Rubin (1977). However the implementation of the EM algorithm requires heavy computation involving numerical integration. Earlier versions of the EM algorithm are given for the one-parameter logit model by Sanathanan and Blumenthal (1978) and for the two parameter probit model by Bock and Aitkin (1981). Part of the current work is an extension and refinement of these earlier applications.

The main work also includes an extension to fuller Bayesian methods by introducing prior distributions on the item parameters. The EM algorithm can be modified for computing posterior modes. The reciprocal of the negative second derivative of the log posterior evaluated at the mode is then used to approximate the posterior covariance matrix of item parameters. The Bayesian approach gives us a means of posterior analysis and opens up new tools for practical problems such as item selection and adaptive testing.

A brief account of the specific accomplishments of this research are summarized below. Fuller write-ups of the technical details are given in the technical reports and other papers listed at the end of this report.

A. Maximum likelihood (m.l.) estimation of item parameters.

1. General setup.

When the ability parameters are assumed to be a random sample from a distrbution with parameter $\underset{\sim}{\gamma}$, the formal likelihood function $\ell(\underset{\sim}{\xi},\underset{\sim}{\gamma})$ becomes a function of the item parameters $\underset{\sim}{\xi}$ and ability distribution parameter $\underset{\sim}{\gamma}$. Under the assumption of local independence, the EM algorithm has been demonstrated as being a powerful tool for deriving the m.l. estimate, $(\hat{\underset{\sim}{\xi}},\hat{\underset{\sim}{\gamma}})$. The computation reduces to working with a series of simpler problems involving one item at a time. For the one parameter logistic with a $N(0,\sigma^2)$ ability distribution, the results are very similar to those obtained by Anderson (1970) using the conditional maximum likelihood approach. Simulation results have shown that estimates usually exist when they do not under the conventional m.l. approach which treats the ability parameter as fixed. Simulations have also suggested that there can be a savings in sample size of 10 - 15% when calibrating items under the one parameter logistic model, relative to the conventional methods. Similar results have been found for ability parameters estimated as posterior means, given $(\underset{\sim}{\xi},\underset{\sim}{\gamma}) = (\hat{\underset{\sim}{\xi}},\hat{\underset{\sim}{\gamma}})$. Details have been published in Rigdon and Tsutakawa (1983).

2. Convergence of the EM algorithm in item response analysis.

Certain questions concerning the convergence of the EM algorithm have been raised in the recent literature. Convergence is guaranteed for the 1-parameter logistic due to convexity properties of the likelihood function. For the two-parameter logistic it can be demonstrated that the EM solution is the solution to the likelihood equation, so that if there is a unique solution it will coincide with the EM solution. Details are presented in Research Report 82-1.

3. Estimation of 2-parameter logistic curves.

Computational details required in the EM algorithm for the 2-parameter logistic model have been derived and illustrated. The nonuniqueness of the parameterization in the 2-parameter model can be eliminated by placing restrictions on the ability prior. In particular, for normal priors on ability, uniqueness is obtained by using the N(0,1) distribution. The asymptotic covariance matrix of the item parameters can be computed using the empirical information matrix. Numerical results based on simulations have indicated the reasonableness of this approach for assessing the posterior uncertainty of the m.l. estimates. Details are presented in Research Report 83-1.

B. Empirical Bayes estimation of item parameters.

In certain situations the item parameters, in addition to the ability parameters, may be treated as a random sample from some prior distribution indexed by an unknown hyperparameter. This situation arises when the item parameters are exchangeable, and the prior information on each item is the same from item to item. Certain ad hoc procedures have been developed for the 1-parameter logistic model. The basic procedure consists of alternately re-estimating the item and ability parameters, which are assumed to be sampled from separate normal distributions with unknown parameters, until convergence is attained. Results were very similar to those derived under A.1. Due to heavy computational requirements, extensions to multiparameter models were not successful. This part of the work is summarized in Rigdon and Tsutakawa (1984).

C. Bayesian estimation of item response curves.

The third and final estimation procedure developed in this project is a fully Bayesian method based on a new family of prior distributions for the item parameter. This family of priors differs from the one proposed by Swaminathan and Gifford (1981), which assumes that item parameters have a common prior whose hyperparameter has a known distribution. The current approach assumes a prior distribution on the probability of correct responses at specified ability levels, for each item separately. This prior then induces a prior on the item parameters. In applications this approach seems simpler than working through the hyperparameters.

The estimation of item parameters is made by using the posterior mode which can be computed via the EM algorithm. The measure of uncertainty is then taken to be the posterior covariance, which can be approximated by the reciprocal of the negative second derivative matrix of the log posterior. Nmerical illustrations for the 2-parameter logistic model have shown that the posterior modes are very similar to the m.l. estimator described under A.2 and these obtained via LOGIST. This illustration was based on a 39 item math test using a sample of 400 subjects. Details are presented in Research Report 84-1.

D. Some unfinished work.

1. Comparison of item response curves.

Two curves can be compared in terms of their logists at different ability levels. In the case of the 2-parameter logistic model, the logits are straight lines. The posterior probability that two such lines are within a given distance over some fixed interval of ability is presented as a measure of the closeness of two lines. This approach differs from the more conventional approach where comparisons are made in terms of the item parameters. Numerical work based on simulated data and actual test data have been completed. Results remain to be written up.

2. Goodness-of-fit study.

A cross validation study was started to examine the predictability of item responses in one data set given observations on a separate but related data set. The test statistics being examined turned out to have power against certain alternative, but not against other alternatives which might be equally important. This phase of the research was discontinued pending a better test statistic.

E. Summary

This research has demonstrated that estimation of item curves with ability parameters treated as a random sample is a promising important approach to item response analysis. Although such modelling has been considered in the past, practical solutions have only recently become a reality with the advent of modern computer technology and the EM algorithm.

This research has focused on the theoretical formulation and solution of maximum likelihood and Bayesian estimations of item parameters. Algorithms have been developed and numerically illustrated for the one and two parameter logistic models. The results are generally comparable to the conventional methods which treat ability parameters as fixed. The current methods have the advantage however of generally producing estimates when they do not exist under older methods. The Bayesian approach yields an approximation to the posterior covariance matrix, which can be used to make probabilistic statements about the uncertainly of the estimated parameters.

Before widespread applications of these results can be realized, it is important that user oriented computer packages be prepared. Such packages should not only handle the case of n subjects and K items, but must be able to deal with missing data and other designs where different subjects may be given different items, as in the case of adaptive testing. For such packages, it would be desirable to include the 3-parameter logistic model, since guessing is an avoidable problem with tests using the multiple choice format which is quite commonly used today.

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Navy

1 Dr. Nick Bond
Office of Naval Research
Liaison Office, Far East
APO San Francisco, CA 96503

1 Lt. Alexander Bory
Applied Psychology
Measurement Division
NAMRL
NAS Pensacola, FL 32508

1 Dr. Robert Breaux
NAVTRAEQUIPCEN
Code N-095R
Orlando, FL 32813

1 Dr. Robert Carroll
NAVOP 115
Washington , DC 20370

1 Dr. Stanley Collyer
Office of Naval Technology
800 N. Quincy Street
Arlington, VA 22217

1 CDR Mike Curran
Office of Naval Research
800 N. Quincy St.
Code 270
Arlington, VA 22217

1 Dr. John Ellis
Navy Personnel R&D Center
San Diego, CA 92252

1 DR. PAT FEDERICO
Code P13
NPRDC
San Diego, CA 92152

1 Mr. Paul Foley
Navy Personnel R&D Center
San Diego, CA 92152

1 Mr. Dick Hoshaw
NAVOP-135
Arlington Annex
Room 2834
Washington , DC 20350

Navy

1 Dr. Norman J. Kerr
Chief of Naval Education and Training
Code 00A2
Naval Air Station
Pensacola, FL 32508

1 Dr. Leonard Kroeker
Navy Personnel R&D Center
San Diego, CA 92152

1 Daryll Lang
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. William L. Maloy (02)
Chief of Naval Education and Training
Naval Air Station
Pensacola, FL 32508

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San Diego, CA 92152

6 Personnel & Training Research Group
Code 442PT
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Arlington, VA 22217

1 Dr. Carl Ross
CNET-PDCD
Building 90
Great Lakes NTC, IL 60088

1 Mr. Drew Sands
NPRDC Code 62
San Diego, CA 92152

1 Mary Schratz
Navy Personnel R&D Center
San Diego, CA 92152

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Navy

1 Dr. Robert B. Smith
Office of Chief of Naval Operations
OP-987H
Washington, DC 20350

1 Dr. Alfred F. Smode
Senior Scientist
Code 7B
Naval Training Equipment Center
Orlando, FL 32813

1 Dr. Richard Snow
Liaison Scientist
Office of Naval Research
Branch Office, London
Box 39
FPO New York, NY 09510

1 Dr. Richard Sorensen
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Frederick Steinheiser
CNO - OP115
Navy Annex
Arlington, VA 20370

1 Mr. Brad Sympson
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Frank Vicino
Navy Personnel R&D Center
San Diego, CA 92152

1 Dr. Ronald Weitzman
Naval Postgraduate School
Department of Administrative
Sciences
Monterey, CA 93940

1 Dr. Douglas Wetzel
Code 12
Navy Personnel R&D Center
San Diego, CA 92152

1 DR. MARTIN F. WISKOFF
NAVY PERSONNEL R& D CENTER
SAN DIEGO, CA 92152

1 Mr John H. Wolfe
Navy Personnel R&D Center
San Diego, CA 92152

Navy

1 Dr. Wallace Wulfeck, III
Navy Personnel R&D Center
San Diego, CA 92152

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Marine Corps

1 Jerry Lehnus
CAT Project Office
HQ Marine Corps
Washington , DC 20380

1 Headquarters, U. S. Marine Corps
Code MPI-20
Washington, DC 20380

1 Special Assistant for Marine
Corps Matters
Code 100M
Office of Naval Research
800 N. Quincy St.
Arlington, VA 22217

1 Major Frank Yohannan, USMC
Headquarters, Marine Corps
(Code MPI-20)
Washington, DC 20380

Army

1 Dr. Kent Eaton
Army Research Institute
5001 Eisenhower Blvd.
Alexandria , VA 22333

1 Dr. Clessen Martin
Army Research Institute
5001 Eisenhower Blvd.
Alexandria, VA 22333

1 Dr. William E. Nordbrock
FMC-ADCO Box 25
APO, NY 09710

1 Dr. Harold F. O'Neil, Jr.
Director, Training Research Lab
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Commander, U.S. Army Research Institute
for the Behavioral & Social Sciences
ATTN: PERI-BR (Dr. Judith Orasanu)
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Mr. Robert Ross
U.S. Army Research Institute for the
Social and Behavioral Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Robert Sasmor
U. S. Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Joyce Shields
Army Research Institute for the
Behavioral and Social Sciences
5001 Eisenhower Avenue
Alexandria, VA 22333

1 Dr. Hilda Wing
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333

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Air Force

1 Dr. Earl A. Alluisi
HQ, AFHRL (AFSC)
Brooks AFB, TX 78235

1 Mr. Raymond E. Christal
AFHRL/MOE
Brooks AFB, TX 78235

1 Dr. Alfred R. Fregly
AFOSR/NL
Bolling AFB, DC 20332

1 Dr. Patrick Kyllonen
AFHRL/MOE
Brooks AFB, TX 78235

1 Dr. Randolph Park
AFHRL/MOAN
Brooks AFB, TX 78235

1 Dr. Roger Pennell
Air Force Human Resources Laboratory
Lowry AFB, CO 80230

1 Dr. Malcolm Ree
AFHRL/MP
Brooks AFB, TX 78235

1 Major John Welsh
AFHRL/MOAN
Brooks AFB , TX 78223

Department of Defense

12 Defense Technical Information Center
Cameron Station, Bldg 5
Alexandria, VA 22314
Attn: TC

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1 Dr. Clarence McCormick
HQ, MEPCOM
MEPCT-P
2500 Green Bay Road
Noorth Chicago, IL 60064

1 Military Assistant for Training and
Personnel Technology
Office of the Under Secretary of Defens
for Research & Engineering
Room 3D129, The Pentagon
Washington, DC 20301

1 Dr. W. Steve Sellman
Office of the Assistant Secretary
of Defense (MRA & L)
2B269 The Pentagon
Washington, DC 20301

1 Dr. Robert A. Wisher
OUSLRE (ELS)
The Pentagon, Room 3D129
Washington, DC 20301

Civilian Agencies

1 Dr. Patricia A. Butler
NIE-BRN Bldg, Stop # 7
1200 19th St., NW
Washington, DC 20208

1 Dr. Vern W. Urry
Personnel R&D Center
Office of Personnel Management
1900 E Street NW
Washington, DC 20415

1 Mr. Thomas A. Warm
U. S. Coast Guard Institute
P. O. Substation 18
Oklahoma City, OK 73169

1 Dr. Joseph L. Young, Director
Memory & Cognitive Processes
National Science Foundation
Washington, DC 20550

Private Sector

1 Dr. Erling B. Andersen
Department of Statistics
Studiestraede 6
1455 Copenhagen
DENMARK

1 Dr. Isaac Bejar
Educational Testing Service
Princeton, NJ 08450

1 Dr. Menucha Birenbaum
School of Education
Tel Aviv University
Tel Aviv, Ramat Aviv 69978
Israel

1 Dr. Werner Birke
Personalstammamt der Bundeswehr
D-5000 Koeln 90
WEST GERMANY

1 Dr. R. Darrell Bock
Department of Education
University of Chicago
Chicago, IL 60637

1 Mr. Arnold Bohrer
Section of Psychological Research
Caserne Petits Chateau
CRS
1000 Brussels
Belgium

1 Dr. Robert Brennan
American College Testing Programs
P. O. Box 168
Iowa City, IA 52243

1 Dr. Glenn Bryan
6208 Poe Road
Bethesda, MD 20817

1 Dr. Ernest R. Cadotte
307 Stokely
University of Tennessee
Knoxville, TN 37916

1 Dr. John B. Carroll
409 Elliott Rd.
Chapel Hill, NC 27514

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Private Sector

1 Dr. Norman Cliff
Dept. of Psychology
Univ. of So. California
University Park
Los Angeles, CA 90007

1 Dr. Hans Crombag
Education Research Center
University of Leyden
Boerhaavelaan 2
2334 EN Leyden
The NETHERLANDS

1 Lee Cronbach
16 Laburnum Road
Atherton, CA 94205

1 CTB/McGraw-Hill Library
2500 Garden Road
Monterey, CA 93940

1 Mr. Timothy Davey
University of Illinhois
Department of Educational Psychology
Urbana, IL 61801

1 Dr. Dattpradad Divgi
Syracuse University
Department of Psychology
Syracuse, NE 33210

1 Dr. Emanuel Donchin
Department of Psychology
University of Illinois
Champaign, IL 61820

1 Dr. Hei-Ki Dong
Ball Foundation
Room 314, Building B
800 Roosevelt Road
Glen Ellyn, IL 60137

1 Dr. Fritz Drasgow
Department of Psychology
University of Illinois
603 E. Daniel St.
Champaign, IL 61820

1 Dr. Stephen Dunbar
Lindquist Center for Measurement
University of Iowa
Iowa City, IA 52242

Private Sector

1 Dr. John M. Eddins
University of Illinois
232 Engineering Research Laboratory
103 South Mathews Street
Urbana, IL 61801

1 Dr. Susan Embertson
PSYCHOLOGY DEPARTMENT
UNIVERSITY OF KANSAS
Lawrence, KS 66045

1 ERIC Facility-Acquisitions
4833 Rugby Avenue
Bethesda, MD 20014

1 Dr. Benjamin A. Fairbank, Jr.
Performance Metrics, Inc.
5825 Callaghan
Suite 225
San Antonio, TX 78228

1 Dr. Leonard Feldt
Lindquist Center for Measurement
University of Iowa
Iowa City, IA 52242

1 Univ. Prof. Dr. Gerhard Fischer
Liebiggasse 5/3
A 1010 Vienna
AUSTRIA

1 Professor Donald Fitzgerald
University of New England
Armidale, New South Wales 2351
AUSTRALIA

1 Dr. Dexter Fletcher
University of Oregon
Department of Computer Science
Eugene, OR 97403

1 Dr. John R. Frederiksen
Bolt Beranek & Newman
50 Moulton Street
Cambridge, MA 02138

1 Dr. Janice Gifford
University of Massachusetts
School of Education
Amherst, MA 01002

Private Sector

1 Dr. Robert Glaser
Learning Research & Development Center
University of Pittsburgh
3939 O'Hara Street
PITTSBURGH, PA 15260

1 Dr. Marvin D. Glock
217 Stone Hall
Cornell University
Ithaca, NY 14853

1 Dr. Bert Green
Johns Hopkins University
Department of Psychology
Charles & 34th Street
Baltimore, MD 21218

1 DR. JAMES G. GREENO
LRDC
UNIVERSITY OF PITTSBURGH
3939 O'HARA STREET
PITTSBURGH, PA 15213

1 Dipl. Pad. Michael W. Habon
Universitat Dusseldorf
Erziehungswissenshaftliches Inst. II
Universitatsstr. 1
D-4000 Dusseldorf 1
WEST GERMANY

1 Dr. Ron Hambleton
School of Education
University of Massachusetts
Amherst, MA 01002

1 Prof. Lutz F. Hornke
Universitat Dusseldorf
Erziehungswissenschaftliches Inst. II
Universitatsstr. 1
Dusseldorf 1
WEST GERMANY

1 Dr. Paul Horst
677 G Street, #184
Chula Vista, CA 90010

1 Dr. Lloyd Humphreys
Department of Psychology
University of Illinois
603 East Daniel Street
Champaign, IL 61820

Private Sector

1 Dr. Steven Hunka
Department of Education
University of Alberta
Edmonton, Alberta
CANADA

1 Dr. Jack Hunter
2122 Coolidge St.
Lansing, MI 48906

1 Dr. Huynh Huynh
College of Education
University of South Carolina
Columbia, SC 29208

1 Dr. Douglas H. Jones
Advanced Statistical Technologies
Corporation
10 Trafalgar Court
Lawrenceville, NJ 08148

1 Professor John A. Keats
Department of Psychology
The University of Newcastle
N.S.W. 2308
AUSTRALIA

1 Dr. William Koch
University of Texas-Austin
Measurement and Evaluation Center
Austin, TX 78703

1 Dr. Thomas Leonard
University of Wisconsin
Department of Statistics
1210 West Dayton Street
Madison, WI 53705

1 Dr. Alan Lesgold
Learning R&D Center
University of Pittsburgh
3939 O'Hara Street
Pittsburgh, PA 15260

1 Dr. Michael Levine
Department of Educational Psychology
210 Education Bldg.
University of Illinois
Champaign, IL 61801

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Private Sector

1 Dr. Charles Lewis
Faculteit Sociale Wetenschappen
Rijksuniversiteit Groningen
Oude Boteringestraat 23
9712GC Groningen
Netherlands

1 Dr. Robert Linn
College of Education
University of Illinois
Urbana, IL 61801

1 Dr. Robert Lockman
Center for Naval Analysis
200 North Beauregard St.
Alexandria, VA 22311

1 Dr. Frederic M. Lord
Educational Testing Service
Princeton, NJ 08541

1 Dr. James Lumsden
Department of Psychology
University of Western Australia
Nedlands W.A. 6009
AUSTRALIA

1 Dr. Gary Marco
Stop 31-E
Educational Testing Service
Princeton, NJ 08451

1 Mr. Robert McKinley
American College Testing Programs
P.O. Box 168
Iowa City, IA 52243

1 Dr. Barbara Means
Human Resources Research Organization
300 North Washington
Alexandria, VA 22314

1 Dr. Robert Mislevy
711 Illinois Street
Geneva, IL 60134

1 Dr. W. Alan Nicewander
University of Oklahoma
Department of Psychology
Oklahoma City, OK 73069

Private Sector

1 Dr. Melvin R. Novick
356 Lindquist Center for Measurement
University of Iowa
Iowa City, IA 52242

1 Dr. James Olson
WICAT, Inc.
1875 South State Street
Orem, UT 84057

1 Wayne M. Patience
American Council on Education
GED Testing Service, Suite 20
One Dupont Circle, NW
Washington, DC 20036

1 Dr. James Paulson
Dept. of Psychology
Portland State University
P.O. Box 751
Portland, OR 97207

1 Dr. Mark D. Reckase
ACT
P. O. Box 168
Iowa City, IA 52243

1 Dr. Lawrence Rudner
403 Ela Avenue
Takoma Park, MD 20012

1 Dr. J. Ryan
Department of Education
University of South Carolina
Columbia, SC 29208

1 PROF. FUMIKO SAMEJIMA
DEPT. OF PSYCHOLOGY
UNIVERSITY OF TENNESSEE
KNOXVILLE, TN 37916

1 Frank L. Schmidt
Department of Psychology
Bldg. GG
George Washington University
Washington, DC 20052

1 Lowell Schoer
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Iowa City, IA 52242

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Private Sector

1 Dr. Kazuo Shigemasu
7-9-24 Kugenuma-Kaigan
Fujusawa 251
JAPAN

1 Dr. William Sims
Center for Naval Analysis
200 North Beauregard Street
Alexandria, VA 22311

1 Dr. H. Wallace Sinaiko
Program Director
Manpower Research and Advisory Services
Smithsonian Institution
801 North Pitt Street
Alexandria, VA 22314

1 Martha Stocking
Educational Testing Service
Princeton, NJ 08541

1 Dr. Peter Stoloff
Center for Naval Analysis
200 North Beauregard Street
Alexandria, VA 22311

1 Dr. William Stout
University of Illinois
Department of Mathematics
Urbana, IL 61801

1 Dr. Hariharan Swaminathan
Laboratory of Psychometric and
Evaluation Research
School of Education
University of Massachusetts
Amherst, MA 01003

1 Dr. Kikumi Tatsuoka
Computer Based Education Research Lab
252 Engineering Research Laboratory
Urbana, IL 61801

1 Dr. Maurice Tatsuoka
220 Education Bldg
1310 S. Sixth St.
Champaign, IL 61820

1 Dr. David Thissen
Department of Psychology
University of Kansas
Lawrence, KS 66044

Private Sector

1 Mr. Gary Thomasson
University of Illinois
Department of Educational Psychology
Champaign, IL 61820

1 Dr. Robert Tsutakawa
Department of Statistics
University of Missouri
Columbia, MO 65201

1 Dr. Ledyard Tucker
University of Illinois
Department of Psychology
603 E. Daniel Street
Champaign, IL 61820

1 Dr. V. R. R. Uppuluri
Union Carbide Corporation
Nuclear Division
P. O. Box Y
Oak Ridge, TN 37830

1 Dr. David Vale
Assessment Systems Corporation
2233 University Avenue
Suite 310
St. Paul, MN 55114

1 Dr. Howard Wainer
Division of Psychological Studies
Educational Testing Service
Princeton, NJ 08540

1 Dr. Ming-Mei Wang
Lindquist Center for Measurement
University of Iowa
Iowa City, IA 52242

1 Dr. Brian Waters
HumRRO
300 North Washington
Alexandria, VA 22314

1 Dr. David J. Weiss
N660 Elliott Hall
University of Minnesota
75 E. River Road
Minneapolis, MN 55455

1 Dr. Rand R. Wilcox
University of Southern California
Department of Psychology
Los Angeles, CA 90007

Private Sector

1 German Military Representative
ATTN: Wolfgang Wildegrube
Streitkraefteamt
D-5300 Bonn 2
4000 Brandywine Street, NW
Washington , DC 20016

1 Dr. Bruce Williams
Department of Educational Psychology
University of Illinois
Urbana, IL 61801

1 Ms. Marilyn Wingersky
Educational Testing Service
Princeton, NJ 08541

1 Dr. George Wong
Biostatistics Laboratory
Memorial Sloan-Kettering Cancer Center
1275 York Avenue
New York, NY 10021

1 Dr. Wendy Yen
CTB/McGraw Hill
Del Monte Research Park
Monterey, CA 93940

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